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What can we learn from the $Z \to b\bar{b}$ vertex?

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Abstract

I stress the fact that a complete study of possible New Physics effects in the $Z \to b\bar{b}$ vertex requires a combined analysis of the ratio $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to hadrons)$ and the longitudinally polarized forward backward asymmetry, A_b.

This is illustrated with a number of models such as the two Higgs-doublet model, the MSSM, Technicolour and models with an extra Z'. The use of effective lagrangean techniques is briefly discussed.

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The remarkable experimental effort done by the LEP collaboration has brought some hadronic processes into the realm of high precision measurements. The best example arises in the ratio $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to hadrons)$ which is now known with an error of the order of 1% ($R_b = 0.2204 \pm 0.0020$). This quantity is a direct measurement of the non oblique vertex correction, since the oblique and QCD corrections cancel in the ratio.

The effective vertex $Z \to b\bar{b}$ can be parametrized in terms of two form factors, the left handed g_L and the right handed g_R:

$$\frac{g}{2\cos\theta_W} Z^\mu \bar{\psi}_b(\gamma_\mu(g_R\gamma_R + g_L\gamma_L))\psi_b \ , \tag{1}$$

where $\gamma_{R,L} = (1 \pm \gamma_5)$. A third form factor, the so called magnetic moment, is neglected.

The effective couplings may be written as $g_{L,R} = g^0_{L,R} + \delta g_{L,R}$ with $g^0_L = -1/2 + 1/3\sin^2\theta_W$ and $g^0_L = 1/3\sin^2\theta_W$. The shifts $\delta g_{L,R}$ contain the effect of the non oblique Radiative Corrections (RC) of the Standard Model (SM), due to the would be goldstone boson exchange and QCD effects due to the non negligible b mass, as well as possible New Physics (NP) effects. In order to determine the two form factors separately we need two independent measurements of the same vertex. One is provided by R_b and the other by the longitudinally polarized forward backward asymmetry defined as :

$$A_b = \frac{\sigma(e_L \to b_F) - \sigma(e_R \to b_F) - \sigma(e_L \to b_B) + \sigma(e_R \to b_B)}{\sigma(e_L \to b_F) + \sigma(e_R \to b_F) + \sigma(e_L \to b_B) + \sigma(e_R \to b_B)} \ , \tag{2}$$

which is directly measured at SLAC [1] as well as in the forward backward asymmetry at LEP [2]. Remarkably A_b depends only on the Z coupling of the b quark [3].

$$A_b = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} \tag{3}$$

The effect of the vertex corrections can be outlined through the ratios of the $Z \to b\bar{b}$ rate and asymmetry to those of the decay $Z \to s\bar{s}$,

$$\frac{\Gamma_b}{\Gamma_s} = 1 + \delta_{bV} \ \text{ and } \ \frac{A_b}{A_s} = 1 + \eta_b \tag{4}$$

We may write δ_{bV} and η_b in terms of the shift $\delta g_{L,R}$ as,

$$\delta_{bV} = -\frac{4(1+b)}{(1+b^2)}[\delta g_L - \frac{(1-b)}{(1+b)}\delta g_R] \tag{5}$$

$$\eta_b = -\frac{4(1-b)(1+b)^2}{b(1+b^2)}[\delta g_R + \frac{(1-b)}{(1+b)}\delta g_L] \ , \tag{6}$$

where $b = 1 - 4/3\sin^2\theta_W$. Thus, δ_{bV} and η_b are naturally orthogonal in the $(\delta g_L, \delta g_R)$ basis, so that the effects that would not contribute to one observable will be revealed by the other one and vice-versa. In particular, the NP effects contributing only to the left handed coupling ($\delta g_R = 0$) imply the correlation $\eta_b/\delta_{bV} = 0.068$. Conversely, for the physics that contributes only to the right handed ($\delta g_L = 0$) one finds $\eta_b/\delta_{bV} = -2.068$. This means that η_b is very sensitive to δg_R whereas δ_{bV} is very sensitive to δg_L.

The leading SM corrections to the $Z \to b\bar{b}$ vertex are very important. They are due to the exchange of the would be Goldstone boson in the t'Hooft-Feynman gauge, and, in the

limit of large top mass ($m_t >> m_W$), are quadratic in m_t contributing only to δg_L [4]. As a consequence any deviation of η_b from zero is a signal of NP.

Using the present value of $m_t = 174 \pm 20$ GeV [5], the LEP data indicate that the SM prediction for R_b might be inconsistent with such a heavy top up to 2.5 σ, and that NP contribution, δ_{bV}^{NP}, must be positive. This initial hint seems very interesting and justifies a thorough investigation of possible NP models providing $\delta_{bV}^{NP} > 0$, together with an analysis of their predictions for η_b.

□ The simplest extension of the SM is the Two Higgs Doublet Model (THDM) in which the electroweak symmetry breaking sector involves two fundamental scalar doublets $H_{1,2}$. The physical spectrum contains an extra pair of charged scalar particles $H^\pm$, a pseudoscalar A^0, and two neutral CP even scalars h^0 and H^0.

The parameter $\tan\beta$, defined as the ratio of the two vevs $< H_1 > / < H_2 >$, allows us to distinguish two different regions for the RC [6]:

1) $\tan\beta \sim 1$: for which the only important contributions come from the $H^\pm$ loops. One finds $\delta g_R = 0$, $\delta g_L \sim 0(m_t^2/M_H^2)$ and consequently $\delta_{bV} < 0$ and $\eta_b \simeq 0$, in contradiction with the previous expectation.

2) $\tan\beta \geq m_t/m_b$: in this region the Yukawa coupling of the b quark can be comparable to that of the t quark so that the process involving intermediate b quark and neutral scalars become important. For the charged sector we find $\delta g_L = 0$, $\delta g_R = 0(m_b^2 \tan^2\beta/M_H^2)$ with $\delta_{bV} > 0$ and $\eta_b \simeq -2\delta_{bV}$. For the neutral sector δg_R and δg_L are $0(m_b^2 \tan^2\beta/M_H^2)$ with $\delta_{bV} > 0$ and $\eta_b \geq 0$. In particular, for a light pseudoscalar A^0, these last contributions can be very large.

□ The next models that I discuss are the SUSY theories . The Higgs sector of the Minimal SUSY model coincides with that of THDM, once the mass relations required by SUSY are imposed. In addition to these contributions discussed above, we also have contributions coming from intermediate states of the superpartners of the SM particles . For light M_{A^0} and large $\tan\beta$ the effect can be important and goes in the right direction, namely, $\delta_{bV} > 0$ and $\eta_b \geq 0$.[6]. These superparticle contributions introduce a lot of new free parameters (the masses of the stop-sbottom left and right and the respective mixing angles, the μ term, and the gaugino masses)[7].

The contribution from the strong interactions involving the gluino are practically negligible. Sizeable corrections can come instead from the stop-chargino sector with

$\delta g_L \simeq 0(m_t^2/(\sin^2\beta M_{SUSY}^2))$ and $\delta_{bV} > 0$ for small $\tan\beta$; and

$\delta g_R \simeq 0(m_b^2 \tan^2\beta/M_{SUSY}^2)$ for large $\tan\beta$, with $\delta_{bV} \simeq -1/2\eta_b < 0$.

For large $\tan\beta$ there are also sizeable contributions from the neutral fermionic supersector (neutralino-sbottom loop) which act along the right experimental direction ,

$\delta g_L \simeq -\delta g_R \simeq 0(m_b^2 \tan^2\beta/M_{SUSY}^2)$ with $\eta_b \simeq -0.3\delta_{bV} < 0$.

In general it is possible to state that, if the discrepancy of R_b is to be explained by the MSSM, then direct observation of superpartners at LEPII or at an upgraded Tevatron can be expected [8].

□ These vertex corrections come out to be very sensitive also to completely different models, like Technicolor, in which the dynamical electroweak symmetry breaking is induced by the vev of bilinear fermion (instead of a fundamental scalar particle).

To provide simultaneously the masses of the W and Z bosons and of the ordinary fermions, additional gauge interactions (Extended Technicolor (ETC)) are introduced.

The effective low energy theory provides a sizeable coupling between the third quark family and the Technifermions inducing a big shift in $\delta g_L \sim O(m_t/4\pi v)$. This implies a negative contribution to δ_{bV}, which is about 8 σ away from the experimental value [12]. Such a negative result, added to the presence of FCNC, puts this models in serious trouble.

Also, in the more popular walking technicolor the effect can be at most a factor 2 smaller [13].

□ Another interesting class of models that can affect this vertex are theories containing extra gauge bosons. When this extra bosons mix with the SM one, the rotation to the mass basis induces a change in the coupling of the physical Z to the fermions which is proportional to $\delta g^f_{LR} \simeq -x m_Z^2/M_{Z'}^2 g^f_{Z'LR}$, where x is a model dependent quantity and $g^f_{Z'LR}$ are the coupling of the extra Z' with the f-fermions.

The limits on the mixing angle of the extra gauge bosons, $\theta = x m_Z^2/M_{Z'}^2$, coupling universally to the fermions (as in Superstring inspired and Gut models) are so strong that the mixing effect on the $Z \to b\bar{b}$ vertex cannot exceed the 1 %.

Recently, some Technicolor inspired models have been explored in which the extra Z' responsible for the generation of the top quark mass couples more strongly to the b_L, t_L and t_R than to the other fermions. The implications of these models are studied in ref.[9] in which it is found that the existence of contributions proportional to $\delta g_L = -\delta g_R$ $(\eta_b/\delta_{bV} \simeq -0.3)$ open a possible reconciliation of the ETC with the experiments.

□ Finally, I would like to discuss an alternative method to investigate the effects of possible NP on the $Zb\bar{b}$ vertex. I will mention only the results of a general investigation that can be found in ref [10], which exploits effective lagrangean techniques. In this approach the Lagrangean is written as $L = L_{SM} + \sum_i f_i O_i/\Lambda^2$, where L_{SM} is the SM Lagrangean, Λ is the scale at which NP appears and O_i are all the gauge and CP invariant operators of dimension 6 which contribute to the RC.

Using the ansatz that the NP generates only operators containing gauge boson fields (11 independent operators) and operators with at least one t_R field (the t_R field is related to the m_t mass) (14 operators) they find that the leading order RC to $Zb\bar{b}$ [of order $0(m_t^2/\Lambda^2 \log\Lambda^2)$] obey the following pattern:

1)only two O_i of the gauge sector and four of the fermionic-t_R sector affect δg_L, thus yielding $\eta_b \simeq 0$;

2)only one operator with one t_R field affects δg_R and, hence, affecting also η_b.

In practice in this formalism a sizeable non zero value of η_b is directly related to the presence of one operator O_{t_R}. However, this technique must be used with care, due to the possible presence of large finite contributions of order O(m_t^2/Λ^2) [11].

In conclusion I have discussed the possible "directions" of NP on the plane (δ_{bV}, η_b) .

In the first quadrant we find the contributions of the THDM, of most part of the parameter space of SUSY models, and of modest Z' contributions; in the fourth quadrant there are instead the extra Z' models inspired by Technicolor and the presence of effects from the O_{t_R} operator.

The next improved measurements of the forward backward asymmetry as well as A_b in SLAC can be of help to disentangle indications of NP.

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